# First-Turn Losses in the LAMPF Proton Storage Ring (PSR)

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*Abstract*

Beam-loss measurements indicate that 0.2 - 0.3% of the protons injected into the PSR are lost during the first turn. We describe a plausible mechanism, involving field stripping of excited hydrogen atoms, for these losses. Protons are injected into the PSR by transporting a neutral hydrogen beam through a hole in the yoke of one ring bender and then through a carbon foil on the ring axis. The foil strips roughly 93% of the beam atoms to protons. Although the original PSR design assumed that all unstripped atoms would pass through a hole in the yoke of the next downstream bender and on to a beam stop, recent calculations [1] indicate that about 6% of these unstripped atoms will emerge from the foil in an excited state with principle quantum number $n \geq 3$. These calculations also indicate that atoms in excited states with $n \geq 3$ will be stripped quickly to protons in the 1.2-Tesla field of the downstream bender. The trajectories of these protons will be outside the phase-space acceptance of the ring and will be quickly lost by collision with the beam pipe, thereby giving rise to first-turn losses. The estimated numbers of protons that would be lost by this mechanism are consistent with the observed first-turn loss rates. This mechanism has important consequences for the design of future storage rings that use neutral atom or negative ion stripping for injection.

## I. INTRODUCTION

Minimization of beam losses is a major goal at the PSR. At the present time the PSR operates with beam loss rates in the range 0.35–0.45 µA, just below 0.50 µA, at which level radioactivation of ring components by the 800-MeV beam begins to make hands-on maintenance unreasonably difficult. Therefore, any reduction of loss rates is highly desirable for mitigation of maintenance problems, and because it would permit raising the average beam current injected into the ring.

Many of the development experiments done at the PSR have been aimed at furthering understanding of the mechanisms that cause beam loss. Two major classes of loss occur: slow losses that would, if acting alone, result in a circulating beam lifetime of thousands of turns; and first-turn losses in which a significant fraction of the injected beam is lost before making one complete revolution around the ring. Slow losses have been understood for some time [2]. They represent the loss of a small fraction of the total circulating beam for each revolution around the ring. Only recently has there emerged a convincing hypothesis to explain the cause of first-turn losses. This paper discusses the new hypothesis.

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This work performed under the auspices of the U.S. Department of Energy.

## II. MEASUREMENT OF BEAM LOSS

Beam losses in the PSR are measured with a system of ten loss monitors located around the outer periphery of the PSR tunnel. The loss monitors are liquid-scintillator-filled cans coupled to photomultiplier tubes. Figure 1 shows a typical beam loss rate pattern recorded during an interval spanning approximately 600 µs of beam injection followed by a 100-µs period during which the beam is allowed to coast without injection of additional beam. There are two components to this loss signal. One is a measure of the slow loss rate. It is proportional to the amount of beam circulating in the ring and increases linearly with time. The other component is a measure of the first-turn loss rate, and is constant during injection because protons are being injected at a constant rate. This component drops to zero at the end of injection.

The total beam loss is proportional to the total area under the curve while the first-turn loss is proportional to the area under constant-width band at the top of the curve. There is a short spike in the loss rate associated with the extraction of the circulating beam from the ring.

Total beam losses are typically 0.6 - 0.7% of the amount of beam injected into the PSR with first-turn losses contributing 0.2 - 0.3 % to this total.

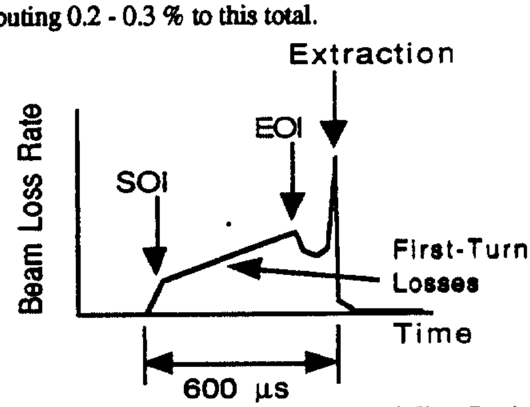


Figure 1. Beam Losses as a Function of Time During and for 100 µs After the End of Injection (SOI = start of injection; EOI = end of injection)

## III. $H^+$ INJECTION INTO THE RING

An understanding of the new hypothesis about the origin of first-turn losses is helped by a brief description of the process by which protons are injected into the PSR. As illustrated in Figure 2, 800-MeV $H^-$ ions are stripped to $H^0$s in a 1.8-Tesla stripper magnet upstream of the ring. The $H^0$s then enter the ring through a hole in a ring dipole magnet. In the ring, $H^0$s are stripped to protons by a 200-µg/cm$^2$ carbon foil located on the ring axis, and the protons then circulate in the ring.

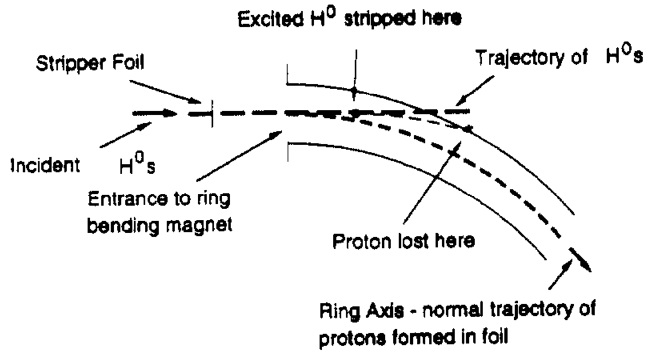


Figure 4. Schematic Illustration of the Process by which Excited $H^0$s Give Rise to First-turn Losses

Table 1. Angular displacement and loss location in ring of protons from stripping of various n states of $H^0$ and estimated yield of the n states

| n | $\Delta\theta$ range (mradians) | Loss location in the ring | Estimated yield from 200-$\mu$g/cm$^2$ |
|---|---|---|---|
| 3 | 22 - 50 | in first dipole | 0.30% * |
| 4 | 6.1 - 12 | after first dipole but in the next 3 ring sections | 0.20% |
| 5 | 1.8 - 4.4 | small fraction lost on ring limiting aperture | 0.15% |

* 1/2 of measured yield from $H^-$ on 200-$\mu$g/cm$^2$ carbon foil

Figure 5 shows the horizontal-plane ring phase-space acceptance ellipse and the $H^0$ beam ellipses at the entrance to the dipole downstream of stripper foil. As an example, the range of angles, taken from Table 1, over which protons from stripped n=4 states are distributed is indicated.

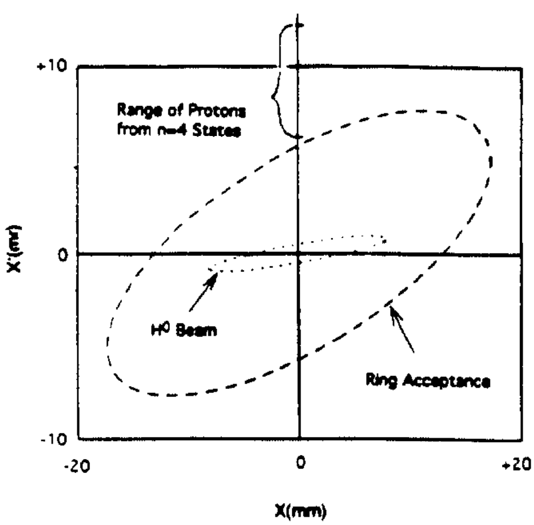


Figure 5. Horizontal-plane Ring Acceptance and Incident $H^0$ Beam Phase-space Ellipses at the Entrance to the Dipole Magnet Downstream of the Stripper Foil

For high n states, lifetimes are short and stripping occurs so early in fringe field of the magnet that the resulting protons follow essentially the same trajectories that protons formed in the foil do. For n=1 and n=2, $H^0$ states are not stripped and continue on to the $H^0$ beam stop.

## V. DISCUSSION OF RESULTS

### *A. Comparison of Measured and Estimated First-Turn Losses*

Experiments [7] have shown that approximately 0.50% of 800-MeV $H^-$s incident on a 200-$\mu$g/cm$^2$ PSR stripper foil are converted to $H^0$s in the n=3 state. Following the plausibility argument of section IV.A., we estimate that approximately 0.25% of the ground-state $H^0$s incident on the foil are converted to $H^0$s in the n=3 state. Assuming that first-turn losses originate primarily from n=3 and n=4 states, and using the yields presented in Table 1, we estimate that the first-turn losses should be approximately 0.4% of the total $H^0$ beam incident on the foil. This is somewhat larger than the 0.3% observed with the loss monitors. However, since a large fraction of the first-turn losses occur inside the first dipole downstream of the foil, the loss monitors will be shielded from the beam spill point by the steel of the magnet, and will provide an underestimate of the actual losses.

### *B. Conclusions and Discussion*

We conclude that the estimated losses are consistent with the measured values, and interpret this fact as support for the hypothesis that excited-state $H^0$s are the cause of the losses.

Since new high-intensity proton storage rings being designed or contemplated involve $H^-$ ion injection through stripper foils, recognition and careful consideration of the consequences of the formation of excited $H^0$s is important for the understanding and control of beam losses.

## VI. REFERENCES


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For each PSR pulse, protons are injected at a constant rate for typically 1675 turns or 600 μs. At the end of injection the circulating proton bunch is extracted and transported to the spallation neutron target at the Los Alamos Neutron Scattering Center (LANSCE).

Approximately 7% of the incident $H^0$s that hit the 200-$\mu g/cm^2$ foil pass through without being stripped to $H^+$s. Most continue undeflected by magnetic fields, and pass out through a hole in the yoke of the downstream dipole magnet and on to a beam stop. However, some exit the foil in excited atomic states and are stripped to $H^+$ in the downstream dipole.

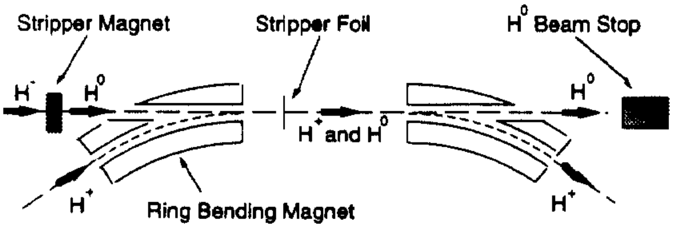


Figure 2. Beam Injection into the PSR

## IV. THE MECHANISM OF EXCITED $H^0$ FORMATION AND PSR FIRST-TURN LOSSES

### *A. Introduction*

Our conjecture is that the presence of excited state $H^0$s emerging from the stripper foil is the root cause of first-turn losses in the PSR. Other work [3] has shown that when 800-MeV $H^-$s pass through thin carbon foils, there are significant numbers of $H^0$s that emerge from the foil in an excited atomic state. In these $H^0$s the electron is relatively weakly bound, and some higher states will be susceptible to field stripping from the atom in the 1.2-Tesla field of the ring dipole magnet downstream of the stripper foil. Field stripping of 800-MeV excited-state $H^-$ ions in magnetic fields was demonstrated in earlier experiments [4]. The same processes will occur when ground-state $H^0$s pass through foils.

### *B. Simple Theory of Excited-State $H^0$ Formation and Field Stripping*

In a simple picture of excited $H^0$ formation, when an 800-MeV ground-state $H^0$ or $H^-$ enters a foil, the electron (or electrons) is stripped from the proton, but continue in near proximity to and at the approximately same speed as the resulting proton. There is a significant probability that an electron will be recaptured into an excited $H^0$ state because the electron(s) and the proton remain relatively near each other in their passage through the remaining thickness of foil. Since, in the case of $H^0$ stripping, there is only one electron following the proton, instead of two as in the case of $H^-$ stripping, it is plausible to assume that the number of excited-state $H^0$s formed from $H^0$ beams will be about half the number formed from $H^-$ beams.

Field stripping of the excited-state $H^0$s can occur because, in the rest frame of the $H^0$, the magnetic field is transformed in part to an electric field that distorts the atomic potential well. If the distortion is large enough, electrons in the higher excited states escape. Simple calculations [1,5] indicate that electrons in energy levels with principle quantum numbers of about three and above are unbound and will be stripped in a 1.2-Tesla field. Figure 3 is an approximate representation of the potential well for an 800-MeV $H^0$, both in zero field and in a 1.2-T magnetic field.

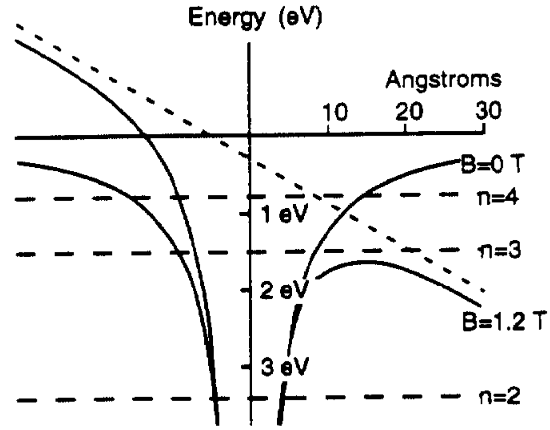


Figure 3. Hydrogen Atom Potential Well Distortion for 800-MeV $H^0$s in a 1.2 -Tesla Magnetic Field

### *C. More Detailed Theory of Excited-State $H^0$ Formation and Field Stripping*

Damburg and Kolosov [6] give a more precise treatment of the Stark splitting of atomic levels for atoms in electric fields (or, equivalently, energetic atoms moving through magnetic fields). This approach allows one to calculate the energy levels and widths, and therefore the lifetimes, of excited $H^0$s that emerge from the stripper foil. These more precise calculations indicate that there are electrons in states with $n \geq 3$ that will be stripped in the dipole magnet downstream of the foil.

The excited $H^0$s entering the first 1.2-tesla dipole downstream of the PSR foil will have finite lifetimes in the field and will, therefore, penetrate part way into the field region before being stripped to protons. Until they are stripped, the $H^0$s will not follow the same trajectories as will protons. Therefore, if an excited $H^0$ progresses far enough into the magnet before stripping, it will not be within the phase space acceptance of the ring, and will be lost on the sides of the ring vacuum pipe within one revolution of the ring, which will cause first-turn losses. This process is illustrated schematically in Figure 4.

Following the treatment of Damburg and Kolosov [6], we find that there are $H^0$ states with principle quantum numbers n=3 and n=4 that strip in the dipole field, but that live long enough so that the resulting proton finds itself outside the phase space acceptance of the ring.

Table 1 summarizes some results of calculations of the fields at which various n states strip. The table also indicates the FWHM range of angles over which the resulting proton trajectories deviate from the center of the ring acceptance ellipse, and indicates yields and proton loss locations.